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Study on method of domestic wastewater treatment through new-type multi-layer artificial wetland

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ABSTRACT

The artificial wetland is comprised of such groundmasses as breakstone and gravel etc as well as aquatic plant attached to it. The wastewater flows in or beneath surface layer of groundmass at the wetland, and decomposes nutritive materials in water through such a serial processes as attachment to groundmass, absorption by plant and microbial conversion etc, which belongs to distinctive soil-plant-microbe system that is differentiated from the wetland. This paper introduces a new-type multi-layer artificial wetland for treatment of domestic sewage, and analyzes the removing effects of COD_{Cr}, BOD_5, NH_3–N, TN and TP in this approach. The results indicate that when hydraulic loading reaches approximately 0.44 $m^3/(m^2\ d)$ and hydraulic retaining duration reaches 3 days, the effect of removing COD_{Cr}, BOD_5, NH_3–N, TN and TP from the wetland is relatively good, and the average removing rate achieves 90.6%, 87.9%, 66.7%, 63.4 and 92.6% respectively, and the effluent COD_{Cr} reaches approximately 14.1~30.8 mg/L, BOD_5 reaches approximately 8.2~13.1 mg/L,NH_3–N reaches approximately 9.9~19.6 mg/L, TN reaches approximately 17.3~28.7 mg/L and TP reaches less than 1.2 mg/L. Thus the effluent exceeds farmland irrigation water quality standards (GB5084-2005). Such factors as planting density, temperature variation and influent contaminant concentration have relatively great correlation with efficiency of wetland treatment. Generally speaking, when the temperature is higher than 24 °C, the higher planting density and lower contaminant concentration reaches, the better effect of the treatment would realize.

Introduction

The artificial wetland is comprised of such groundmasses as break stone and gravel etc as well as aquatic plant attached to it. The wastewater flows in or beneath surface layer of groundmass at the wetland, and decomposes nutritive materials in water through such a serial processes as attachment microbe system that is differentiated from the wetland [1–3]. In spite of the history on groundmass, absorption by plant and

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microbial conversion etc, which belongs to distinctive soil-plant wastewater treatment for artificial wetland has been lasting for more than 100 years, especially the research has extensively been initiated recently for more than 30 years [4–7], but there still has been deficient in systematic and in-depth research on rural domestic wastewater treatment for subsurface flow artificial wetland.

So far, many advanced techniques and experiences have been accumulated in the field of household sewage treatments. In recent years, with the rapid development of economy, the increasing deteriorations of water environments have already impaired people's health and economy's sustainable developments. Consequently, some reasonable and useful techniques have been studied and applied regarding household sewage treatment [8,9].

Currently, with respect to the treatments of urban household wastewater, the scholars both from China and foreign countries have focused on the following techniques: constructed wetland ecological treatment system, high-rate algal pond (HRAP), subsurface wastewater infiltration system, anaerobic treatment system, small-scale household wastewater purification system, the combined techniques, and so on [10–12].

Constructed wetland ecological treatment system

As inspired by the simulations on natural wetland, the wastewater purification in a constructed wetland ecological treatment system is achieved by the triple synergistic effects of physical, chemical and biological interactions in natural ecosystems. By filling a certain level of paddings (such as gravels) into a depression with a certain length-width ratio and surface slope, we construct a wetland system. Subsequently, various plants are cultivated on the filled bed, which are characterized by favorable treatment performance, high survival rate, strong water-resistance behavior, long growing period, beautiful appearance and high economic value (such as reed, zizania aquatica, acorus calamus *etc*.). A unique ecological environment with animals and plants is then formed, including the cultivated plants, the existent animals in water and paddings and microorganisms. When flowing through the surface and gaps in the filled bed, the wastewater can be filtered, absorbed, deposited, ion-exchanged, assimilated by plants and decomposed by microorganisms, with an ultimate aim of achieving high-efficient sewage purifications. According to the differences in engineering design and water flow pattern, the constructed wetland treatment system can be classified into surface flow wetland (SFW), vertical flow wetland, tidal flow wetland and SFW, in which SFW has been applied most widely [13,14].

High rate algae pond technique

HRAP is a modified technique developed on the basis of the traditional stabilization pond, which has been advanced by Oswald, a professor from the University of California [15]. The common species in HRAP are chlorella, scenedesmus, cyclotella, micractinium, chlamydomonas, euglena, and so on. The species of algae depends on the species, concentration and temperature of nutrients, as well as the stirring method. The algal-bacterial symbiosis system in an HRAP presents more rich biofacies compared with the system in a common stabilization pond. In an HRAP, the wastewater can be mixed thoroughly by a continuous stirring device. Besides, the O_2 and CO_2 concentrations in the pond can be adjusted while the water temperature and quality can be balanced, contributing to the removal of organic matters, nitrogen, and phosphorus. Siegrist et al. [16] have conducted studies on the changes of pollutant concentrations in one day, and investigated their effects on the rural household sewage treatments in an HRAP. The contrast experiments have been performed on two HRAPs, which located in an identical environment but varied in hydraulic retention time. The experimental results indicates that Suspended solids(SS) and COD concentrations of effluents are higher at non than them at dawn, while the Total nitrogen(TN) and Total phosphorus(TP) concentrations present different variation tendencies, which are related to the daily variations of Dissolved oxygen(DO) and pH value. The daily variations of pollutant concentrations are of minor influences on the system's reliability. Al-Shayji et al. [17] have placed a sedimentation basin followed an HRAP, and therefore, the algae generated in the wastewater treatment process can be collected in the basin and used for afforestation and fertilizer-increasing for poor soils. However, the settleability of algae is significantly affected by the climate and operation parameters, i.e., 20%~30% of algae will be lost without a suitable environment [18].

Subsurface wastewater infiltration system

Subsurface wastewater infiltration system is based on the ecological principles in nature, in which the wastewater is discharged into the constructed soil layer. The soil layer, with an excellent diffusion capability, locates at about 50 cm away from the ground surface. The effluents slowly flow through the rubbles and sand layer around the arranged water pipes, and then diffuse into the surrounding soil layer induced by capillarity effects in soils. Accordingly, the pollutants in sewage can be filtered, absorbed and degraded by a large number of microorganisms in surface soils [19,20]. In a subsurface wastewater infiltration system, the natural purification capability can be reasonably and fully utilized. Moreover, the technique is less affected by the varying seasons and the effluent quality is stable. The FILTER sewage treatment system is a typical subsurface wastewater infiltration system, in which filtration and land treatment are combined with the subsurface pipe drainage [21]. The wastewater is firstly used for crop irrigation, and finally discharged by the buried pipes after land treatments. The FILTER system can meet the water and nutrient requirements of crops, and more importantly, the nitrogen and phosphorous contents in wastewater can be reduced to a certain extent. The effects of sewage constituents and organic loading on the clogging in soils have been studied by PEI Liang et al. [22], and the results suggest that the clogging in the filter layer is significantly related to the organic matter contents in the surface. Generally, the clogging appears in the upper layer at a few millimeters above the soil substrate.

As can be concluded, both the contents of Chemical oxygen demand(CODcr) and SS exert great influences on the filter layer. The wastewater is required to be of low CODcr and SS contents in a substrate wastewater infiltration system.

Anaerobic biological treatment system

Anaerobic biological treatment system is referred as to the transformation process of organic matter into methane and carbon dioxide by facultative anaerobic and anaerobic microbial population, under anaerobic conditions, which is also called as anaerobic digestion. By contrast with land treatment technology, anaerobic treatment is characterized by high-load device, small occupied area and few generated sludge. Meanwhile, large amounts of resources are produced. According to Cille's research, the anaerobic treatment technique can be more economic only when the CODcr content in sewage exceeds 4000 mg/L. Nevertheless, with the increasing shortage of resources, this technique has been developed and improved steadily, now exhibiting more outstanding advantages. More and more scholars have turned their attentions towards the studies of anaerobic treatment on low-concentration sewage, and therefore a lot of achievements have been gained both in laboratories and practical applications [23,24].

Elodie et al. [25] have designed a sewage treatment method based on an anaerobic membrane, and a kind of PU foam paddings have been added to the wastewater. The results indicate that the SS can be removed effectively by the clean paddings, even when the hydraulic retention time is below 0.5 h and the upstream velocity exceeds 10 m/h. The anaerobic membrane bioreactors have been also adopted by Elodie Passeporta et al., Ting Zhang et al. [26] by which the household wastewater can be disposed appropriately.

Conclusively, the hydraulic retention time and sludge retention time can be separated by adding paddings into the anaerobic membrane bioreactor. Even under a short hydraulic retention time, the pollutants can be removed efficiently, which has greatly promoted the applications of anaerobic membrane bioreactor.

Combined techniques

The buried unpowered purification devices and biogas technology for household sewage purification are proved to be poor in the removal of nitrogen and phosphorus. Currently, the effluent processed by a single technique can hardly meet the increasingly stringent standards for the discharge of nitrogen and phosphorous. A common method is to combine several techniques, with the purpose of strengthening nitrogen and phosphorous removal capacities. The combined techniques which are widely applied include ‘the anaerobic tank/subsurface flow wetland system [27,28] the anaerobic/waterfall aeration contact oxidation/constructed wetland system ’, ‘the anaerobic trickling filter/constructed wetland system’, ‘the anaerobic filter/oxidation pond/ecological canal system’ and *etc*. The frontal processing units mainly aim at the removal of organic matters and some nutrient substances, while the subsequent units focus on the further removal of nitrogen and phosphorus.

As stated above, the multi-technique treatment systems have various advantages, such as low energy consumption, convenient operation and maintenance, low requirements on infrastructure, lost operating costs, high adaptability on inflow loading and favorable effluent quality. Therefore, the combined techniques are regarded as the low-cost and high-efficiency methods to control non-point pollution. However, in the practical applications, the occupied land area will be very large if we design a system in accordance with the normal hydraulic loading. The system will also be susceptible to the climatic changes, and the substrates are likely to be blocked. Besides, the treatment effects and construction costs are tightly related to the kind of paddings, the methods and depths of filling. As a consequence, studies on how to improve the system loading, reduce the occupied area and solve the problems of substrate clogging will be the focus in further work.

Artificial wetland is not only used for the domestic sewage treatment in small town, but also adopted for agricultural pollution and industrial wastewater treatments etc. Presently, the treatment technology based on artificial wetland overseas has made a major advance in domestic sewage and waste water treatment from aquaculture, animal husbandry, oil refining, mining, tanning and eutrophication [29–33].

The paper adopts ecological treatment system based on artificial wetland as primary technology. The system is mainly composed of matrix, wetland plants and microorganisms; the three of which major factors have their own distinctive sewage purification capability. Wetland matrix is to provide a carrier for the microorganisms and also adsorb and intercept the pollutant part: wetland plant is to utilize pollutant in sewage as nutritive material necessary for self-growth and also deliver oxygen to the root area in order to therein form special micro-ecological environment and further enhance the wetland system's purification capacity. The microorganisms are the main undertakers to degrade pollutant in wetland system, under the joint action of which artificial wetland system is to achieve efficient sewage purification. The functional sewage purification mechanism in artificial wetland is quite complicated. The research shows that ecological treatment system based on artificial wetland is to achieve sewage purification under the action of matrix, wetland plant and various microorganisms in terms of physics, chemistry and biology [34,35].

This paper introduces a domestic wastewater treatment system with simple operation procedure for multi-layer artificial wetland in wastewater treatment with short process, fast speed, good water quality, big ratio of enrichment, low cost, less consumption of energy as well as the irrigation with reclaimed water after treatment can both save fertilizer and freshwater resources, thus which enjoys bright prospect in extensive utilization.

Experiment

The paper presents the adopting artificial wetland system as a treatment process, including:

(1) Organic matter removal. Artificial wetland is able to efficiently degrade organic pollutant where the water insoluble organic pollutants in sewage are removed by

interception, precipitation and microbiological degradation while the soluble organic ones are to be removed by assimilation and absorption at plant root together with the biodegradation of the microorganisms attached to the plant root and the matrix surface.

(2) Nitrogen removal. Nitrogen pollutants in sewage include organic Nitrogen ammonia together with a little nitrogen nitrite and nitrogen nitrate quantity. Some organic Nitrogen is microbiologically degraded in inorganic nitrogen for the plants growth. Some organic Nitrogen attached to suspended solid is thereby removed by precipitation and filtration; it also is hydrolyzed to amino acid and further decomposed into NH4+–N. In the final analysis, the primary approach to remove Nitrogen in sewage includes ammonia volatilization, Nitrogens biological removal, and plant and microbe absorption.

(3) The Phosphorus removal. The sewage Phosphorus exists in the form of organic phosphate, polyphosphate and phosphate etc. Therefore, organic phosphate and polyphosphate are to be turned into phosphate by means of hydrolysis and microbiological degradation. When pH value is about 7, phosphate is in dissolved state, existing in the form of di-hydrogen phosphate. In artificial wetland system, Phosphorus is removed by three major approaches: namely the microbiological assimilation and absorption, the chemical matrix precipitation and the plant assimilation.

Experimental unit & method

The experiment is applied to subsurface flow artificial wetland with vertically upward flow and compound structure(see Fig. 1). The trapezoid concreted pond is designed of 160 cm height, upper bottom with 3 m length, lower bottom with 1.7 m length, boulder layer with 20 cm thickness, gravel stone layer with 30 cm thickness, coal dust - furnace cinder mixed layer with 40 cm thickness and soil layer with 30 cm thickness, totaling 120 cm thickness for filling materials. Cross wall with the height of 140 cm is set up in influent water storage pond and which with the height of 120 cm is set up in influent water sedimentation basin, the cross wall of influent water sedimentation basin is based on boulder layer with which influent pipe of the basin is partially connected with. In addition, cross wall with the height of 100 cm is set up in effluent water sedimentation basin and which with the height of 80 cm is set up in effluent water storage pond. Furthermore, particle diameter of boulder keeps to 1.9–3.6 cm and that of gravel stone keeps to 0.7–1.8 cm. The process abides by such operating principles as leading domestic wastewater flowing firstly into wastewater sedimentation basin for settlement, and then flowing into influent water storage pond before overflowing and infiltrating into multi-layer filling material zone through influent pipe, i.e. entering filling material zone through beneath cross wall of influent sedimentation basin, passing from bottom to top through boulder layer, gravel stone layer, coal dust-furnace cinder mixed layer and soil layer for filtration. The overflowing water flows into effluent sedimentation basin through cross wall before overflowing into effluent water storage pond. In addition, the wetland is evenly covered with Ba-Mao or reed. Perforated pipes and sampling pipes are vertically embedded along the centerline of ponds and basins so as to conduct water sampling and measure out such parameters as dissolved oxygen, temperature and pH value etc inside the wetland. The experimental unit shows good operational aspect after the commissioning between May–August 2011.

Experimental item & method

The rural domestic wastewater is applied to this experiment as untreated water, and the water quality and analytic method are shown in Table 1 below:

Results & analysis

Effect of removing COD_{Cr} & BOD_5

It's discovered by the experiment that the temperature and crop planting have relatively obvious correlation with the effect of removing COD_{Cr} and the 5th biochemical oxygen demand

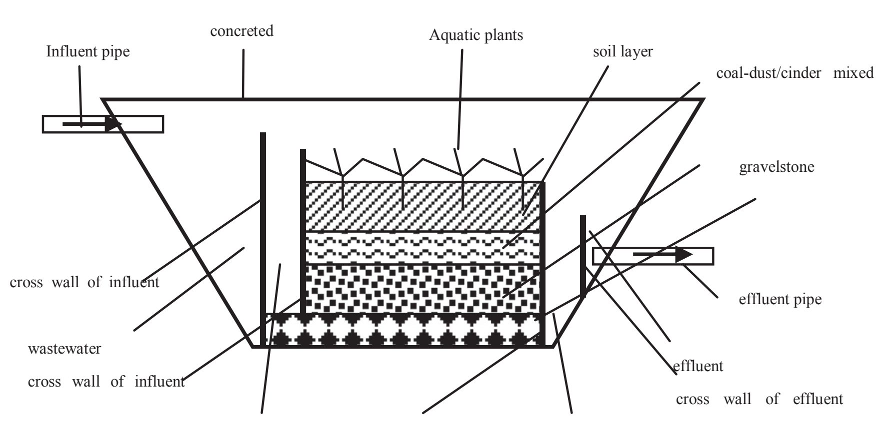

Fig. 1 – Structure of multi-layer.

Table 1 – Experimental items, methods & water quality.

Item	Value	Analytic method
COD_{Cr} (mg L^{-1})	213~381	Dichromate process
BOD_5(mg L^{-1})	103~207	Dilution inoculation
NH_3–N(mg L^{-1})	48~112	Nessler's reagent
TN (mg L^{-1})	71~104	Ultraviolet spectrophotometry
TP (mg L^{-1})	4.8~12.1	Aluminic acid spectrophotometry
T/°C Temperature/°C	18~31	Thermometer
pH	5~9	Glass electrode method

(BOD5) in multi-layer artificial wetland. When the wetland is densely planted with reeds and the temperature is higher than 20 °C, the rate of removing COD_{Cr} from the wetland is relatively high. It can be seen from Figs. 2 and 3 that the correlation between the temperature & crop planting and the effect of removing COD_{Cr} from the wetland. Whereas the temperature above 20 °C is favorable for microbe's proliferation and growth, as well as provides high microbial activity, strong ability to absorb and decompose organic matter, thus the densely planted crop could absorb more and more organic matters in the wastewater, and the crops with highly developed root system can strongly absorb organic matter [12]. Furthermore, when the wetland is densely planted with reeds and the temperature is higher than 22 °C, the rate of removing COD_{Cr} from the wetland reaches 86.7%–93.2%, keeping average rate of removal to 90.6%. During the experiment lasting for several months, the COD_{Cr} in influent shows relatively higher fluctuation, but the COD_{Cr} in effluent keeps to between 14.1 and 30.8 mg/L. Moreover, it's discovered by the experiment under the condition of densely planted reeds on the wetland that the temperature has relatively obvious correlation with the effect of removing BOD_5 from the wetland. It can be seen from Fig. 2 that the ecosystem shows relatively good effect of removing BOD_5 from the wetland when the temperature inside the wetland is higher than 22 °C, and the rate of removing BOD_5 keeps to between 76.3 and 91.5%, keeping average rate of removal to 87.9%. Meanwhile, the BOD_5 in effluent keeps to between 8.2 and 13.1 mg/L, which is superior to farmland irrigation water quality standards (GB5084-2005) [36].

This experiment also discovers that the rate of removing COD_{Cr} and BOD_5 would gradually declines [37]after long-run

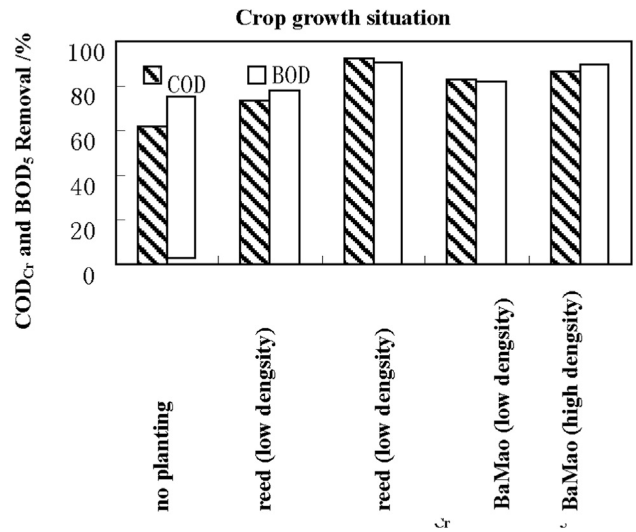

Fig. 3 – Removal rate effect of COD_{Cr} with plant growth.

test under like conditions, which probably because that a majority of organic matters inside the wetland were absorbed by plant root and biomembrane attached to the surface of filling materials, and subsequently which was gradually decomposed by microbe, as well as partial organic matters fail to contact with filling material before carrying out by effluent due to decrease of hydraulic loading [38].

Effect of removing ammonia nitrogen

It's discovered by the experiment that the temperature and crop planting have relatively obvious correlation with the effect of removing NH_3–N from multi-layer artificial wetland. The rate of removing NH_3–N from the wetland is relatively high when there are densely planted Ba-Mao and the temperature is above 24 °C. It can be seen from Figs. 4 and 5 that the correlation between the temperature & planting arrangement and the effect of removing NH_3–N from the wetland, as well as suitable temperature is favorable for microbe's proliferation, growth, high activity and removal of ammonia

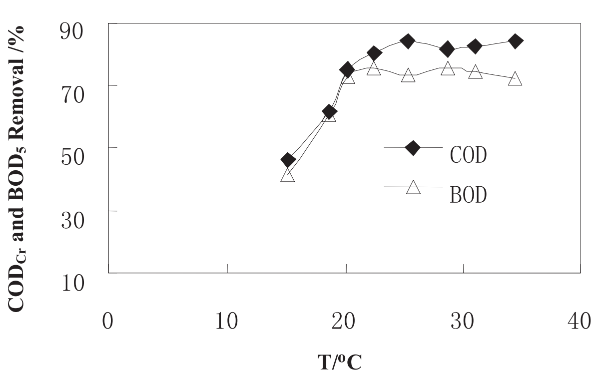

Fig. 2 – Removal effect of COD_{Cr} and BOD_5 with temperature.

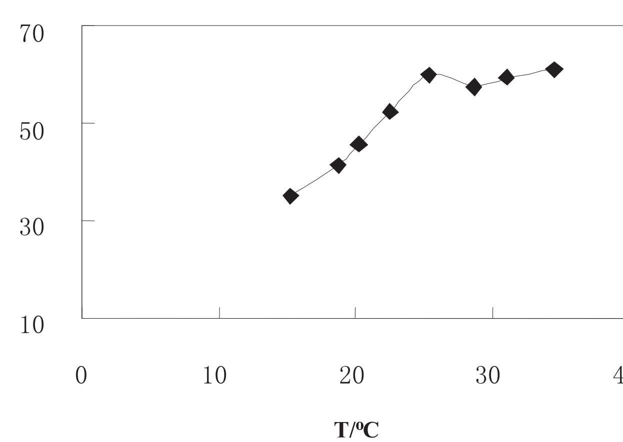

Fig. 4 – Removal rate effect of NH_3–N with temperature.

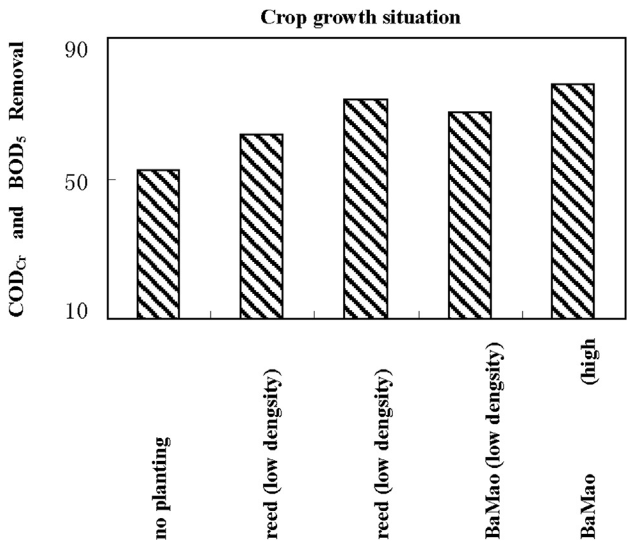

Fig. 5 – Removal rate effect of COD_{Cr} with plant growth.

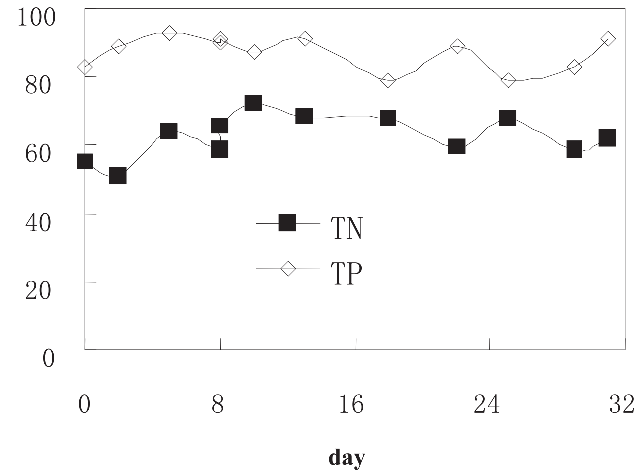

Fig. 6 – Removal rate effect of TN and TP.

nitrogen. Therefore, crop root system could further absorb NH_3–N and TN in the wastewater under the condition of densely planting method.

When the wetland is densely planted with Ba-Mao and the temperature is above 24 °C, the rate of removing NH_3–N from the wetland keeps to between 63.2%–79.1%, keeping average rate of removal to 66.7%. In addition, the NH_3–N in effluent keeps to between 9.9 and 19.6 mg/L during the experiment lasting for several months, which is superior to farmland irrigation water quality standards (GB5084-2005) [36] It's also discovered by the experiment that along with the extension of the system running duration and decrease of system hydraulic loading, the untreated water retains longer in wetland system and which would be liable to turn the system to anaerobic state, this phenomenon would inhibits nitrification and results in lower rate of removing NH_3–N. When hydraulic loading is excessively great and hydraulic power stays too short to reach generation duration in demand of nitrobacter, partial nitrobacter would be liable to flow out of the system along with water current, which would inhibits nitrification and results in slightly decline of rate of removing NH_3–N [38] Therefore, wetland system needs to be repeatedly flushed by clean water after running for a period of time.

Effect of removing TN & TP

The approaches for removing nitrogen and phosphorus from artificial wetland mainly include absorption by aquatic plant, nitrification and denitrification of microbe, absorption by ground substance and ion exchange. Among which, the amount of nitrogen absorbed by wetland plants and ground substance is limited, and nitrification and denitrification of microbe are the most important approaches. However, removing phosphorus from wetland is mainly depended upon the absorption by ground substance [39].

The results of study on the effect of removing TN and TP from multi-layer artificial wetland under the condition of densely planting with reeds and the temperature above 22 °C are shown in Fig. 6 below. The average rate of removing TN is 63.4% and TN in effluent keeps to between 17.3 and 28.7 mg/L, as well as TP in effluent is averagely less than 1.0 mg/L, which is superior to farmland irrigation water quality standards (GB5084-2005) [36].

Removing TP from wetland is mainly depended upon absorption and decomposition by microbe, absorption by plant and physical & chemical action of filling material [34], but gradual increase of hydraulic loading will be unfavorable for that and would result in decline in the rate of removal. Yet, it's also indicated by other study that the rate of removing TN and TP soars to maximum value along with the increase of hydraulic loading before gradual decline [40]. It can be seen from the experimental results that the rate of removing TN and TP increases from the first day to 8th day, but begins to lower on the 10th day. After flushing the wetland with clean water on the 18th day, the rate of removal increases during subsequent days.

Conclusion

It achieves very good effect to substitute artificial wetland for primary and secondary sedimentation basin in conventional activated sludge treatment. When wastewater flows through whole system, the plants in artificial wetland could absorb organic matters in the wastewater, which would be both favorable for the plants growth and effective reclamation of organic matters in the wastewater, turning organic matters in the wastewater into useful resources. Therefore, this wastewater treatment system can provide not only high-efficient ability to decompose organic matters without secondary pollution, but also realize clean production and provide new approach for wastewater treatment in the future. The conclusion is detailed as follows:

(1) For rural domestic wastewater treatment through multi-layer artificial wetland, the effect of removing COD_{Cr}, BOD_5, NH_3–N, TN and TP from the system is

relatively good when hydraulic loading reaches approximately 0.44 $m^3/(m^2$ d), hydraulic power retains for 3 days, COD_{Cr} shows 213–381 mg/L, BOD_5 shows 103–207 mg/L, NH_3–N shows 48–112 mg/L, TN shows 71–104 mg/L and TP shows 4.8–12.1 mg/L and water temperature is above 25 °C.

(2) The average rate of removing COD_{Cr}, BOD_5, NH_3–N, TN and TP from multi-layer artificial wetland is 90.6%, 87.9%, 66.7%, 63.4 and 92.6% respectively, and COD_{Cr} in effluent approximately keeps to between 14.1 and 30.8 mg/L, BOD_5 approximately keeps to between 8.2 and 13.1 mg/L, NH_3–N approximately keeps to between 9.9 and 19.6 mg/L, TN approximately keeps to between 17.3 and 28.7 mg/L and TP keeps less than 1.2 mg/L, which is superior to farmland irrigation water quality standards (GB5084-2005).

(3) The effect of treatment through wetland has relatively great correlation with such factors as planting arrangement, temperature variation and influent contaminant concentration etc. Generally speaking, when the temperature is above 24 °C, the higher density of planting adopts and the lower influent contaminant concentration keeps, the better effect of wastewater treatment would realize.

Existing problems & suggestions

(1) It's proposed to apply relatively longer running and observation to the utilization due to shorter experimental duration and being failed to acquire regeneration period of ground substance.

(2) In order to research the correlation between the plant and the effect of wastewater treatment, it's proposed to conduct the test of plant purifying effect under the basis of the experiments mentioned above because that this pilot study belongs to simulation experiment and it's failed to conduct experiment to confirm purifying effect of the plant in artificial wetland.

(3) This orthogonal experiment lacks in repeated tests due to limited duration, it's proposed to conduct repeated tests under the basis of experiments mentioned above so as to further verify the accuracy and reappearance of the experimental results.

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